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REVISION OF STANDARDS FOR ATTENUATION MEASUREMENTS OF SHIELDED ENCLOSURES

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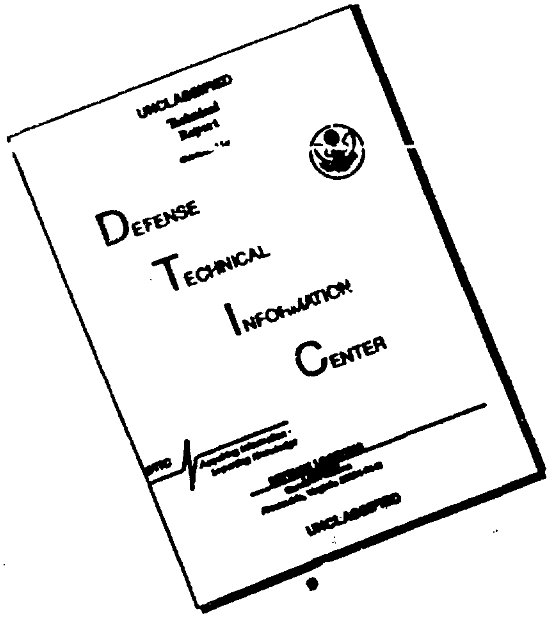

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REVISION OF STANDARDS FOR
ATTENUATION MEASUREMENTS OF SHIELDED ENCLOSURES

ABSTRACT

This report covers the work done during the second quarter of a one-year research program which began on 18 June 1958. The program consists of theoretical and experimental investigation leading to an improved standard for testing shielded enclosures in the frequency range of 14 kilocycles to 10,000 megacycles.

To date, the theoretical phase of the program has been devoted to a review of the literature concerned with shielding theory and the compilation of a report summarizing the results of this investigation. Plane-wave shielding theory is concerned with the penetration of an infinite planar surface by a plane-wave. This approximation to the shielding problem yields results which are conceptually and mathematically simple. The fact that at low frequencies an actual enclosure does not approximate an infinite surface, and the fields normally encountered are not plane-wave, makes the accuracy of its application questionable.

The similarity between plane-wave propagation and propagation in a transmission line makes it possible to apply the results of transmission-line theory to the plane-wave theory of shielding. These results could, however, be obtained directly from extension of the plane-wave theory of shielding. The transmission-line analogy is especially useful in determining shielding effectiveness when the fields encountered have impedances which differ considerably from that of a plane wave.

Several investigators have considered the problem of determining the field which exists inside a shell of conducting material when the shell is immersed in a plane-wave field. Approximate formulae have been developed which give the intensity of the field inside of the shell in terms of that of the external field when the wavelength is large compared to the dimensions of the shell. Spherical and cylinderical shells have been considered.

The shielding theories mentioned thus far involve the use of mode functions and depend for their simplicity on the fact that the geometries of the enclosures and incident fields considered conform to the coordinate surfaces of common coordinate systems. A significantly different theory of shielding makes use of moving images to duplicate the effects of eddy currents induced in the shield by the incident field. The result of this theory is an integral formula which gives the vector potential of the electromagnetic field generated by eddy current.

A shielded enclosure is subject to electromagnetic fields whose frequencies and impedances vary over wide limits. Sources characterized by large currents and small charge displacements produce low impedance fields at near distances while high impedance fields are produced by sources having converse characteristics. A typical source of a low impedance field is a current loop. The field of a loop is usually derived using the dipole approximation which applies at large distances from the loop. Tests of enclosures make use of loops at near distances. The exact field of a loop at low frequencies can be derived by direct integration, and the results indicate the dipole approximation to be valid even at fairly close distances. A short electric dipole provides a high impedance field and is commonly used to test the effectiveness of shielded enclosures against such fields.

Thus far, examination of the literature has not revealed a theory of shielding which takes into account door or wall joints. Furthermore, the theories advanced to predict the effectiveness of screen and laminated materials are approximate. It would be desirable to have a test which measures the effectiveness of such materials and joints against fields having a well defined impedance and structure. The TEM mode in a coaxial guide has the same impedance as a plane wave and the field inside is simple and well defined. It can be shown that in theory a barrier in the guide will respond in the same manner as a planar surface subject to a plane wave. For this reason a coaxial testing device, for testing shielding materials and joints, has been constructed and is undergoing tests. This device has the advantage that the testing field is confined to the region within the coaxial structure, thereby simplifying the measurement problem.

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REVISION OF STANDARDS FOR
ATTENUATION MEASUREMENTS OF SHIELDED ENCLOSURES

I. PURPOSE

The purpose of this research is to develop improved techniques for measuring the effectiveness of shielded enclosures in the frequency range 14 kilocycles to 10,000 megacycles per second and to provide recommendations for standard methods of evaluating such enclosures.

II. GENERAL FACTUAL DATA

A. Identification of Personnel

Name	Title	Man-Hours
R. B. Schulz	Research Engineer-Project Engineer	188
L. C. Peach	Research Engineer	443
L. J. Greenstein	Technical Assistant	96

B. References

The following references have been used during this quarterly period.

(1) "Electromagnetic Theory", J. A. Stratton, McGraw-Hill Book Co., New York, N. Y., 1941.

(2) "Theory, Design and Engineering Evaluation of Radio-Frequency Shielded Rooms", C. S. Vasaka, Report No. NADC-EL-54129, U. S. Naval Air Development Center, Johnsville, Pennsylvania.

(3) "Electromagnetic Waves", S. A. Schelkunoff, D. Van Nostrand Company, Inc. New York, N. Y., 1947.

(4) "Electromagnetic Shielding at Radio Frequencies", L. V. King, The London, Edinburgeh, and Dublin Philosophical Magazine and Jornal of Science, S. 7., Vol. 15, No. 97, Feb. 1933.

(5) "Static and Dynamic Electricity", W. R. Smythe, McGraw-Hill Book Co., Inc., 1950.

(6) "Antennas', Theory and Practice", S. A. Schelkunoff and H. T. Friis,

John Wiley and Sons, Inc., New York, N. Y., 1952.

(7) MIL-STD-285, 25 June 1956.

C. Meetings and Conferences

Date: October 3, 1958

Place: Armour Research Foundation

Personnel Attending:

Mr. L. W. Thomas, Bureau of Ships

Mr. M. Epstein, Armour Research Foundation

Mr. L. J. Greenstein, Armour Research Foundation

Mr. L. C. Peach, Armour Research Foundation

Mr. R. B. Schulz, Armour Research Foundation

The organization of the project was discussed. Mr. Thomas indicated that during the course of the project a complete bibliography of literature pertinent to shielded enclosures should be compiled. He also agreed that the work of ARF should be synchronized with the activities of the newly-formed IRE Sub-committee 27.5 which is concerned with the formulation of standards for shielded enclosures. It was pointed out that progress on the project has been limited because of the delays encountered in receiving government-furnished equipment.

III. DETAILED FACTUAL DATA

A. Introduction

The purposes of shielded enclosures are either to provide a space which is as free as possible from extraneous electromagnetic fields or to confine such fields to a specified area. Tests designed to measure the effectiveness of enclosures should provide information which directly or indirectly

indicates the ability of the enclosure to perform this function. This implies that the logical formulation of a testing procedure must involve consideration of the normal use of the enclosure.

Attempting to formulate a test of enclosure effectiveness based on "normal use" is made difficult by the fact that the enclosure is required to operate over a large range of frequencies (14 kc to 10 kmc) and field impedances (several hundredths of an ohm to several megohms). This wide variation makes it difficult to specify "normal use". Thus, although in theory a test based on "normal use" is very desirable, it may be difficult to formulate practically.

There are several approaches which can be adopted in formulating a suitable test procedure:

(1) The enclosure can be tested under one or more sets of "typical operating conditions" where "conditions" refers to the characteristics of the electromagnetic field that the enclosure has to confine to, or exclude from, a given area.

(2) It can be tested under one or more sets of "worst" operating conditions where "worst" refers to conditions which represent the greatest problems in shielding.

(3) It can be tested under a standarized set of operating conditions (even though these conditions are not normally encountered), thereby providing data which makes it possible to predict the operation of the room under other operating conditions.

The study has not progress sufficiently to make a decision regarding which (or some combination) of the approaches should be adopted. The choice will depend upon a number of factors including:

(1) The feasibility of developing an analytical method which will make it possible to use the results from tests performed under one set of operating conditions to predict the operation of the room under a different set of conditions.

(2) The practicability of generating certain operating conditions (electro-magnetic fields) in a region of reasonable extent.

For this reason the theoretical phase of the program has been concerned initially with compiling information concerning shielding theory. The results of this investigation to date, are given in Section III. B.

Subsequent sections of the report will reveal that the theory of shielding against plane-wave electromagnetic fields can be formulated in elementary terms. For this reason a plane-wave field might prove to be a good standard field with which to evaluate shielded enclosures. It is difficult to generate a confined field having the impedance of a plane-wave field at reasonable distances from the source. There is every indication, however, that a coaxial line can be used to generate such fields and that the shielding effectiveness of various materials can be tested in a coaxial configuration. A coaxial holder has been constructed to develop the technique and is undergoing tests. A description of the holder is given in Section III. C. 1.

The theoretical analysis of a shielded enclosure requires that, in the analysis, the enclosure be replaced by some regular geometric figure which is more or less representative of that of the enclosure. Furthermore, the location and characteristics of the wall and door joints will usually be neglected. These, and other simplifications, will cause the results of the analysis to be approximate. Consequently, whatever the results of the theoretical investigation, tests on an actual enclosure will be necessary. The equipment required to perform these tests is being constructed; see Section III. C. 2.

B. <u>Theoretical Investigation</u>

1. <u>Shielding Theory</u>

a. <u>Plane-wave theory of shielding</u>

A theory of shielding which is conceptually and mathematically simple is the plane-wave theory. The model for this theory is a plane-wave impinging

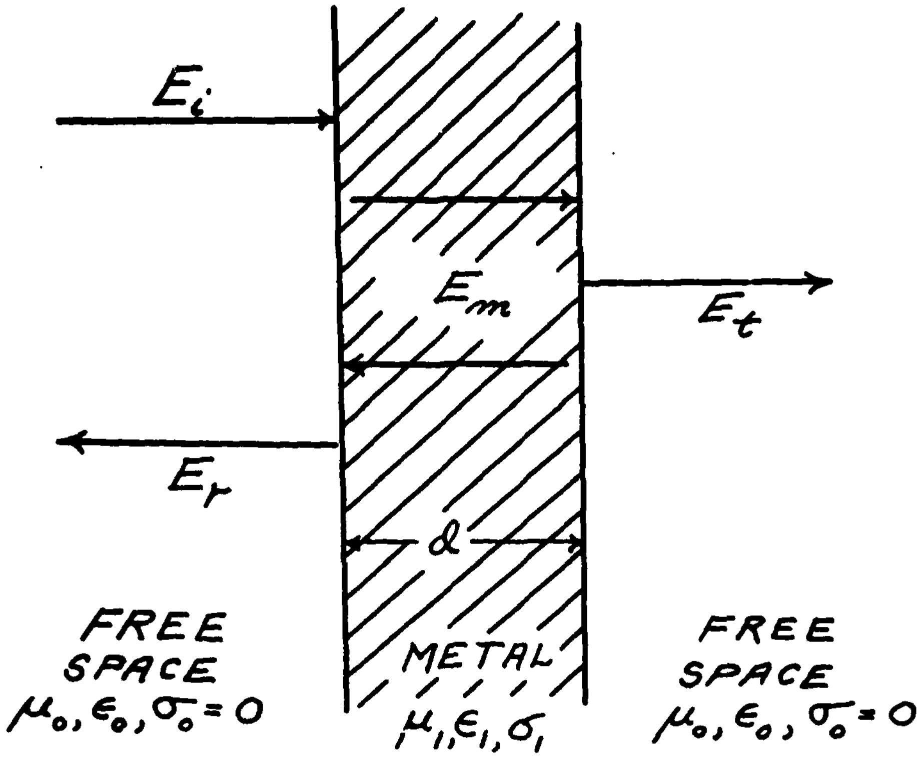
normally on an infinite planar sheet. The ratio of the amplitude of the transmitted to the incident wave is taken as a measure of the shielding effectiveness of the sheet. This situation, illustrated in Figure 1, is considered in detail in the literature[1]. Maxwell's equations are solved in the three regions, to left of, within, and to the right of the sheet subject to the condition that the fields are invariant in two dimensions. The solutions have the form of plane waves. The amplitudes of the waves are obtained in terms of the amplitude of the incident wave by requiring the total magnetic and electric fields to be continuous across the boundaries between the sheet and free space. The ratio of the amplitude of the transmitted to the incident wave is given in Figure 1. It is evident that this model, which forms the basis for the bulk of shielding theory, can be readily extended to take into account situations involving multiple parallel sheets.

b. Transmission-line analogy

The method of analysis employed in the plane-wave, planar-sheet model parallels the solution of the uniform transmission line. This similarity suggests that the concepts and formulae developed in transmission line theory can be applied to plane-wave shielding theory[2]. This analogy is illustrated in Figure 2. The solutions in both cases are seen to consist of forward and backward traveling waves. In plane-wave shielding theory, the metallic sheet generates a reflected wave because the wave impedance in the metal differs from the impedance in free space. This situation can be duplicated in transmission line theory by inserting a section of line, having a different characteristic impedance, into a transmission line. In plane-wave theory the amplitudes

[1] Reference 1: pages 511-513.

[2] Reference 2.



$$\frac{E_t}{E_i} = \left| \frac{4Z_{12}}{(Z_{12}+1)^2 e^{j(\beta_o-\gamma_1)d} - (Z_{12}-1) e^{j(\beta_o+\gamma_1)d}} \right|$$

$$Z_{12} = \frac{\mu_o \gamma_1}{\mu_2 \beta_o}$$

$$\beta_o = \omega \sqrt{\mu_o \epsilon_o}$$

$$\gamma_1 = \omega \sqrt{\mu_1 \epsilon_1} \left(1 + \frac{\sigma_1}{j\omega\epsilon_1}\right)^{1/2}$$

FIGURE 1. PENETRATION OF AN INFINITE PLANAR SHEET BY A PLANE WAVE

Plane Wave Shielding Theory

$$\nabla \times \mathbb{E} = -\mu \frac{\partial \mathbb{H}}{\partial t}$$

$$\nabla \times \mathbb{H} = \sigma \mathbb{E} + \epsilon \frac{\partial \mathbb{E}}{\partial t}$$

$$\nabla \cdot \mathbb{B} = 0 , \nabla \cdot \mathbb{D} = \rho \quad \mathbb{B} = \mu \mathbb{H}$$

$$\mathbb{D} = \epsilon \mathbb{E} \quad \mathring{\ell} = \sigma \mathbb{E}$$

Give the one dimensional equation

$$\frac{d^2 E_z}{d y^2} = j^2 \omega^2 \mu \epsilon \left(1 + \frac{\sigma}{j\omega\epsilon}\right) E_z$$

$$\mathbb{E} = E_x 1_x + E_y 1_y + E_z 1_z$$

which has a solution

$$E_z = E_z^+ e^{j\gamma y} + E_z^- e^{-j\gamma y}$$

$$\gamma^2 = \omega^2 \mu \epsilon \left(1 + \frac{\sigma}{j\omega\epsilon}\right)$$

The magnetic field is

$$H_x = \frac{-\gamma}{\omega\mu}\left(E_z^+ e^{j\gamma y} - E_z^- e^{-j\gamma y}\right)$$

$$\mathbb{H} = H_x 1_x + H_y 1_y + H_z 1_z$$

and the wave impedance is

$$Z_w^+ = \frac{E_z^+}{H_x^+} = -\frac{\omega\mu}{\gamma}, Z_w^- = \frac{-E_z^-}{H_x^-} = -\frac{\omega\mu}{\gamma}$$

Transmission Line Theory

$$\frac{\partial V}{\partial x} = RI + L\frac{\partial I}{\partial t}$$

$$\frac{\partial I}{\partial x} = GV + C\frac{\partial V}{\partial t}$$

Give the equation

$$\frac{d^2 V}{d x^2} = j^2 \omega^2 LC \left(1 + \frac{G}{j\omega C}\right) V$$

which has a solution

$$V = V^+ e^{j\gamma_T x} + V^- e^{-j\gamma_T x}$$

$$\gamma_T^2 = \omega^2 LC \left(1 + \frac{G}{j\omega C}\right)$$

The current is

$$I = \frac{-\gamma_T}{\omega L}\left(V^+ e^{j\gamma_T x} - V^- e^{-j\gamma_T x}\right)$$

and the characteristic impedance is

$$Z_T^+ = \frac{V^+}{I^+} = -\frac{\omega L}{\gamma_T}, Z_T^- = \frac{-V^-}{I^-} = -\frac{\omega L}{\gamma_T}$$

FIGURE 2. TRANSMISSION LINE ANALOGY

of reflected and transmitted waves were derived in terms of the amplitude of the incident wave by requiring continuity of the magnetic and electric fields. Similarly in the transmission line case, continuity of the voltage and current is imposed in deriving the amplitudes of the waves. This direct correspondence between plane-wave shielding and transmission lines has enabled many of the results of transmission line theory to be used in the solution of shielding problems. It should be pointed out however that these results could have been obtained directly in the plane-wave theory. It will be pointed out subsequently that the transmission line analogy can also be applied to obtain approximate solutions to shielding problems which are not plane-wave in nature.

c. Shielding in non-planar configurations

The shielding theory discussed thus far has been restricted to the case of plane waves impinging normally on an infinite planar sheet. The results of the theory are only partially applicable since the electromagnetic waves encountered in practice do not generally resemble a plane wave and the enclosure geometry does not approximate an infinite plane. The feature of the electro-magnetic field, which varies over wide limits in practice, is its impedance. It should be emphasized that a plane wave has only one impedance which is a function of the constitutive parameters of the space. The results of plane-wave shielding theory have been extended to non-plane wave fields in the following manner[3]. It is demonstrated that certain current distributions having regular geometrical shapes (line and small loop currents) generate one dimensional fields having impedances which vary considerably from that of a plane wave. It is further demonstrated that when the conductivity of the shield surrounding the current distribution is high, the propagation of the field through

[3] Reference 3: pages 303-315.

the shield is very nearly plane-wave. This fact makes it possible to apply the transmission-line analogy. Thus, the extensions to shielding theory discussed above consist of:

(1) Generating electromagnetic fields having impedances which differ from that of a plane wave.

(2) Assuming that the propagation of this field through the shield is very nearly plane-wave so that the transmission-line analogy can be applied.

The plane-wave theory of shielding and its transmission-line analog have been used in calculations of shielding effectiveness when the fields are those due to a loop or dipole. It will be demonstrated that these sources generate fields which have impedances that are respectively lower and higher than that of a plane-wave. In such cases the solution involves the assumption that these fields consist of plane waves having impedances different from that of a true plane wave in the same media.

The penetration of a plane wave into a thin shell, having a regular geometrical shape whose dimensions aresmall compared to a wavelength, has been investigated and the results are formulae giving the degree of penetration[4]. The geometries which have been considered are spherical and cylindrical shells. The complete analysis is lengthy and will not be repeated here. The general method employed is to expand the incident wave (plane-wave) in a sum of mode functions which are consistent with the geometry of a shell. The unknown field due to currents excited in the shell is expanded in terms of these same mode functions with unknown amplitude coefficients. The total field is written as a sum of the two expansions and the boundary conditions imposed on the total field. The magnitude of the amplitude coefficients are calculated and the total fields inside and outside of the shell are thus obtained. It should be noted

[4]Reference 4.

that these solutions are obtained readily because the geometry of the shell is taken to be a coordinate surface of a common coordinate system. The method employed in solving the plane-wave planar shield problem is essentially that described above. However, in that case the mode functions are extremely simple and consist of only forward-and backward-traveling waves.

d. Moving image theory of shielding

The discussion thus far has treated three approximations to the shielding problem:

(1) The shielding of a plane wave by an infinite planar surface and the transmission-line equivalent to this problem.

(2) The generation of fields having impedances different from that of a plane wave and application of plane-wave shielding theory to these fields.

(3) The penetration of plane-waves into shells having regular geometrical shapes.

As previously indicated, these solutions have all employed mode functions with varying degrees of approximation. An approach to shielding which is significantly different employs the use of moving images. Since the techniques employed in this approach differ from those used in most other investigations of shielding theory, it is deemed advisable to examine it in detail. The material given below is from the reference cited[5] and is presented in somewhat more detail in the hope of clarifying the development in the reference.

Faraday's law in differential form is given by

(1) $$\nabla \times \mathbb{E} = -\frac{\partial \mathbb{B}}{\partial t}$$

[5]Reference 5: pp.402-408.

The equation $\nabla \cdot \mathbb{B} = 0$ implies the existence of a magnetic vector potential $\mathbb{A}$ defined by

$$(2) \quad \nabla \times \mathbb{A} = \mathbb{B}$$

These equations yield

$$(3) \quad \nabla \times \left(\mathbb{E} + \frac{\partial \mathbb{A}}{\partial t} \right) = 0$$

which implies the existence of a scalar potential Φ defined by,

$$(4) \quad \nabla \Phi = -\mathbb{E} - \frac{\partial \mathbb{A}}{\partial t}$$

Consider a thin, planar metallic sheet in the $x\,y$ plane, Figure 3. The vector quantities in (4) can be decomposed into components which are perpendicular to (in the z direction), and parallel to, the sheet. The z components satisfy the equation,

$$(5) \quad E_z = \frac{-\partial A_z}{\partial t} - (\nabla \Phi)_z$$

The sheet is thin so that the charges which collect on the surfaces of the sheet generate a $(\nabla \Phi)_z$ which cancels out $\frac{\partial A_z}{\partial t}$ causing E_z to go to zero. This is equivalent to stating that there are no eddy currents in the z direction. Hence only the tangential quantities

$$(6) \quad E_T = -\frac{\partial A_T}{\partial t} - (\nabla \Phi)_T$$

are of interest. For large thin sheets the term $(\nabla \Phi)_T$ is of no consequence. Furthermore, E_T is given by

$$(7) \quad E_T = R_T\, i_T$$

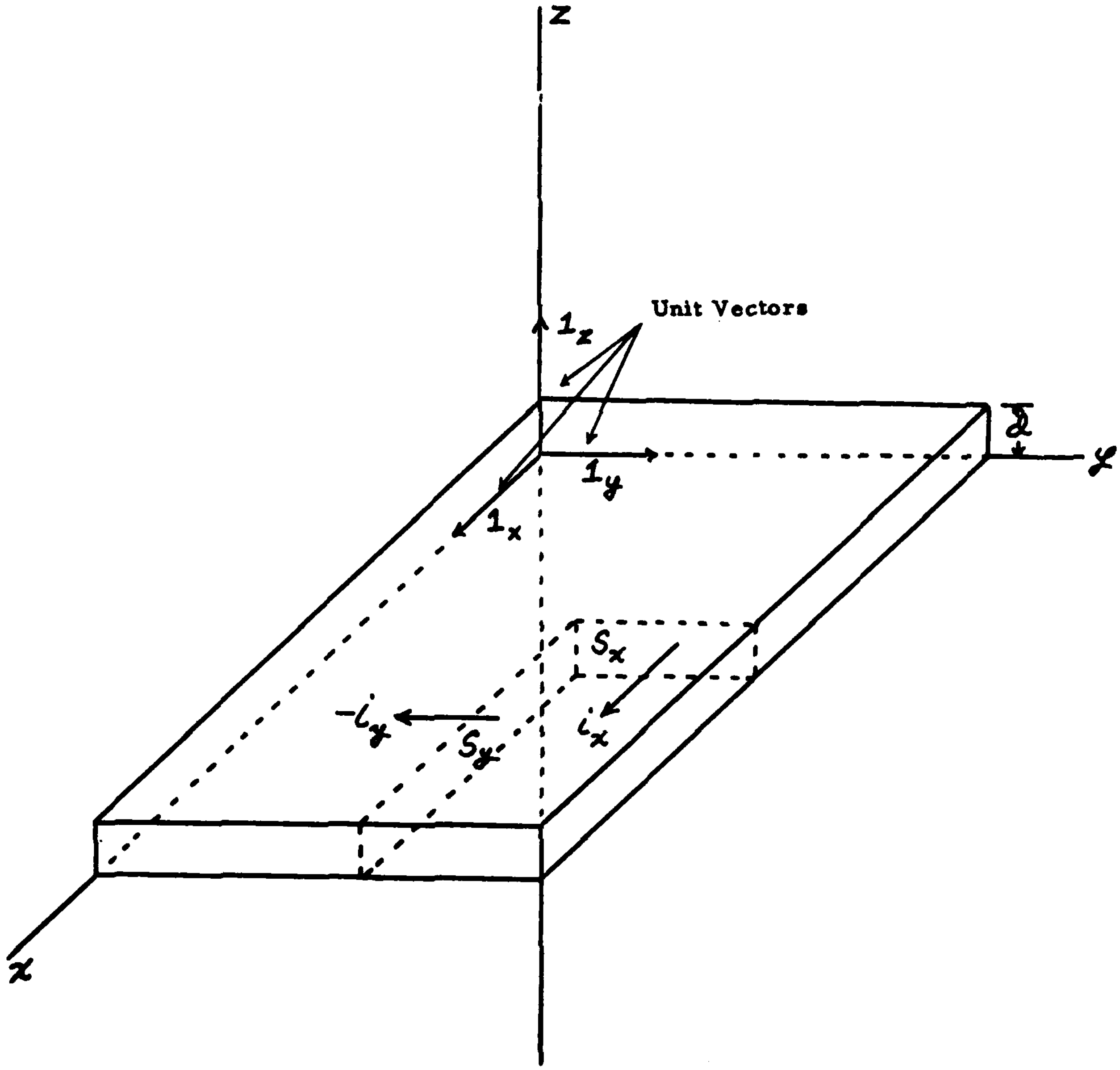


FIGURE 3. SOLUTION TO SHIELDING PROBLEM BY THE USE OF MOVING IMAGES

where i_T is the tangential current density and R_T is the surface resistivity

(8) $$R_T = \frac{R}{d}$$

The symbol R represents the bulk resistivity of the material comprising the sheet and d is the thickness of the sheet. The total vector potential is due to the applied vector potential A_{T1} and an induced vector potential A_{T2} resulting from eddy currents. These considerations cause (6) to take the form

(9) $$-\frac{\partial(A_{T1}+A_{T2})}{\partial t} = R_T\, i_T$$

A stream function $W(x,y)$ is defined which is equal to the total current flowing through a cross section (for example S_x or S_y) of the sheet extending from (x,y) to the edge of the sheet, Figure 3. Consider the Maxwell equation

(10) $$\nabla \times \mathbb{H} = \mathbb{i} + \frac{\partial \mathbb{D}}{\partial t}$$

which in integral form is

(11) $$\iint \nabla \times \mathbb{H} \cdot d\mathbb{S} = \iint \mathbb{i} \cdot d\mathbb{S} + \epsilon \frac{\partial}{\partial t} \iint \mathbb{E} \cdot d\mathbb{S}$$

For harmonic fields this equation becomes

(12) $$\iint \nabla \times \mathbb{H} \cdot d\mathbb{S} = \iint \mathbb{i} \cdot d\mathbb{S} + j\omega\epsilon R \iint \mathbb{i} \cdot d\mathbb{S}$$

In shielding materials $\omega\epsilon R$ is much less than unity. This fact combined with Stokes theorem yields

$$(13)\quad \oint \mathbf{H}\cdot d\mathbf{l} = \iint \mathbf{i}\cdot d\mathbf{S}$$

Using the definition of $W(x,y)$ and $\mathbf{B}=\mu\mathbf{H}$, (13) takes the form

$$(14)\quad \oint \mathbf{B}\cdot d\mathbf{l} = \mu\, W(x,y)$$

Since that part of $\mathbf{B}$ due to W is symmetric, and using $\mathbf{B}=B_x 1_x + B_y 1_y$ it follows that

$$(15)\quad 2\int_x^{\infty} B_x(\xi,y)\,d\xi = 2\int_y^{\infty} B_y(x,\eta)\,d\eta = \mu\, W(x,y)$$

Differentiation of (15) and use of the definition of $W(x,y)$ yields

$$(16)\quad \mu\frac{\partial W}{\partial x} = -2B_x(x,y) = -\mu\, i_{Ty} = 2\frac{\partial A_{yz}}{\partial z}$$

and

$$(17)\quad \mu\frac{\partial W}{\partial y} = -2B_y(x,y) = \mu\, i_{Tx} = -2\frac{\partial A_{xz}}{\partial z}$$

which when combined result in

(18) $$i_T = -\frac{2}{\mu}\frac{\partial A_{T2}}{\partial z}$$

This equation when combined with (9) yields

(19) $$\frac{\partial (A_{T1} + A_{T2})}{\partial t} = \frac{2 R_T}{\mu}\frac{\partial A_{T2}}{\partial z}$$

Because of the continuity of the vector potential, the right hand side of (19) is finite which requires that the left hand side of (19) also be finite. This implies that $\mathbb{A}_1 + \mathbb{A}_2$ cannot change abruptly. Hence, if the applied vector potential $\mathbb{A}_1$ is changed suddenly, eddy currents will immediately flow in such a manner as to generate an $\mathbb{A}_2$ that will tend to keep the total vector potential in the sheet constant.

Following the development in the reference, let a source in the region $z > 0$, Figure 3, give rise to an applied vector potential $\mathbb{A}_1$. This applied vector potential (due to a change in the source) changes at time $t = 0$ and is given by $\mathbb{A}_{1-}$ for $t < 0$, and $\mathbb{A}_{1+}$ for $t > 0$. The preceding discussion indicated that $\mathbb{A}$ in the sheet must be continuous at time $t = 0$ hence at time $t = 0$ eddy currents will be set up which tend to keep the vector potential constant in the sheet and in the region $z < 0$. The vector potential due to the eddy currents must therefore be equal to the difference between the applied vector potential immediately prior to and following $t = 0$. That is

(20) $$\mathbb{A}_2 = \mathbb{A}_{1-} - \mathbb{A}_{1+}$$

where A_2 is the vector potential produced by the eddy currents generated at $t = 0$. It is evident that the potential produced by eddy currents could have been produced by image sources which give rise to A_{1-} and $-A_{1+}$. To summarize, if sources in the region $z > 0$ which give rise to A_{1-} (for $t < 0$) are changed at $t = 0$ so that they now give rise to A_{1+} (for $t > 0$), then at $t = 0$ eddy currents will flow such as to maintain the vector potential in the sheet and in the region $z < 0$ equal to A_{1-}. Furthermore, the effect of the eddy currents can be duplicated by the introduction of image sources which give rise to A_{1-} and $-A_{1+}$.

The eddy currents, which are produced at $t = 0$, will decay and the nature of this decay can be determined by solving the differential equation given by (19), and utilizing (20) as an initial condition. The solution has the form.

$$(21)\quad A_2 = A_{1-}\left(x, y, -|z| - \frac{2R_T}{\mu}t\right) - A_{1+}\left(x, y, -|z| - \frac{2R_T}{\mu}t\right)$$

This equation indicates that the vector potential due to eddy currents could be produced by image sources which at $t = 0$ produce A_{1-} and $-A_{1+}$ and which recede from the sheet with velocity $2R_T/\mu$

The previous discussion has concerned itself with a situation in which the applied vector potential was A_{1-} for all $t < 0$ and A_{1+} for all $t > 0$ hence A_1 was not variable in time except at $t = 0$. Let the applied field now be given by $A_1(x, y, z, t)$ at time t. Then the change in A_1 which occurs in a time interval $d\tau$ is given $\frac{\partial A_1}{\partial t}d\tau$ and as has been shown, this is equal and opposite to the vector potential produced by eddy currents generated by this change in applied field. This

vector potential due to eddy currents decays in the manner indicated by (21).

The vector potential due to eddy currents can thus be replaced by image sources which are generated as the applied field changes and which travel away from the sheet. At some time t_1 the applied field undergoes a change which causes images to be formed. The vector potential produced by these sources is given by

$$(22)\quad dA_2 = \frac{\partial A_1(t_1, x, y, z)}{\partial t} d\tau$$

At a time interval τ later this vector potential is given by

$$(23)\quad dA_2 = \frac{\partial A_1(t_1, x, y, -|z| - \frac{2R_I}{\mu}\tau)}{\partial t} d\tau$$

The value t_1 is just $t - \tau$ hence (23) becomes

$$(24)\quad dA_2 = \frac{-\partial A_1(t-\tau, x, y, -|z| - \frac{2R_I}{\mu}\tau)}{\partial t} d\tau$$

This is actually the contribution to the induced vector potential at time t which results from the formation of image sources which were produced as a result of a change in the applied field at a previous time interval. Thus, the vector potential due to eddy currents which exists at a time t is due to all the previously formed image sources and is given by

$$(25)\quad A_2 = -\int_0^\infty \frac{\partial A_1(t-\tau, x, y, -|z| - \frac{2R_I}{\mu}\tau)}{\partial t} d\tau$$

In the region which is on the opposite side of the sheet from that containing the sources of the applied field it can be shown that (25) can be transformed to

$$(26)\quad A_1 + A_2 = \frac{2R_T}{\mu}\frac{\partial}{\partial z}\int_0^\infty A_1\left(t-\tau, x, y, z-\frac{2R_T}{\mu}\tau\right)d\tau$$

Thus, the image method of solution yields a value for the vector potential on the side of the shielding surface opposite to the sources. There are two points worthy of additional comment. The method does not distinguish between reflection and attenuation and furthermore, the μ which appears in the integral is that of the shielding material.

It can be shown that the application of this integral formula to the case of two coaxial loops separated by a shielding surface yields the result,[6]

$$(27)\quad N = \frac{6R_T c}{\omega\mu(a^2+b^2+c^2)}$$

where c is the distance between the loops and a and b are the radii of the loops.

The symbol N represents the ratio of flux linkages in the loop being shielded in the absence and presenc e of the shielding surface. The units employed are MKS. The formula can also be written as

$$(28)\quad N = \frac{20.3\,R_r c}{f d\mu_r(a^2+b^2+c^2)}$$

[6] Reference 5: page 408.

where f = frequency in cycles per second

d = thickness in inches

a, b = radii of loops in inches

C = distance between loops in inches

R_r = resistivity of material relative to copper

μ_r = relative permeability

The above formula is only applicable for

$$f \gg \frac{.173 R_r}{\mu_r d} \tag{29}$$

The preceding formula has been developed without the use of mode functions (as was the case in other developments of shielding theory). Its accuracy remains to be determined by experimental measurement. It should be noted that the use of the integral formula

$$A_1 + A_2 = \frac{2R_T}{\mu} \frac{\partial}{\partial z} \int_0^\infty A_1\left(t-\tau, x, y, z - \frac{2R_T}{\mu}\tau\right) d\tau \tag{30}$$

is not restricted to shielding against fields arising from loops. Its use for other types of interference fields remains to be investigated.

2. Generation of Standard Fields

a. Low-impedance sources

The amount of reflection which occurs at a shielding surface is dependent upon the relative impedance of the electromagnetic field incident on the surface and the impedance of a wave in the shielding material. For this reason, it is of interest to examine impedances of several typical sources.

The impedance of an electromagnetic field is the ratio of the electric to the magnetic field intensities. The relative intensities of these fields is determined by the relative amount of current and charge displacement in the source. Sources incorporating a large current and small charge displacement result in low impedance fields while sources having converse current and charge characteristics result in high impedance fields.

A common source used to generate low impedance fields is the magnetic loop. The conventional method of deriving the fields due to a loop assumes the validity of the dipole approximation[7]. The fields due to a loop which result from the use of this expression are shown in Figure 4. The radial impedance, E_ϕ / H_θ, is also shown. The field due to a mangetic loop can be derived by direct integration if the frequency is low[8]. The formulae due to a loop for this approximation are given in Figure 5.

A test of shielded enclosures which employs loops involves two coplanar loops oriented in the manner shown in Figure 6[9]. It is of interest to compare the impedances for the field at the surface of the shield using the dipole and low frequency approximations. The fields and hence the impedance will vary over the surface of the sheet so that a complete spatial comparison of the two approximations would be complex. A comparison can be made, however, in the $Z = 0$ plane. For $Z = 0$, $H_\rho = 0$ and the approximations result in the following impedances,

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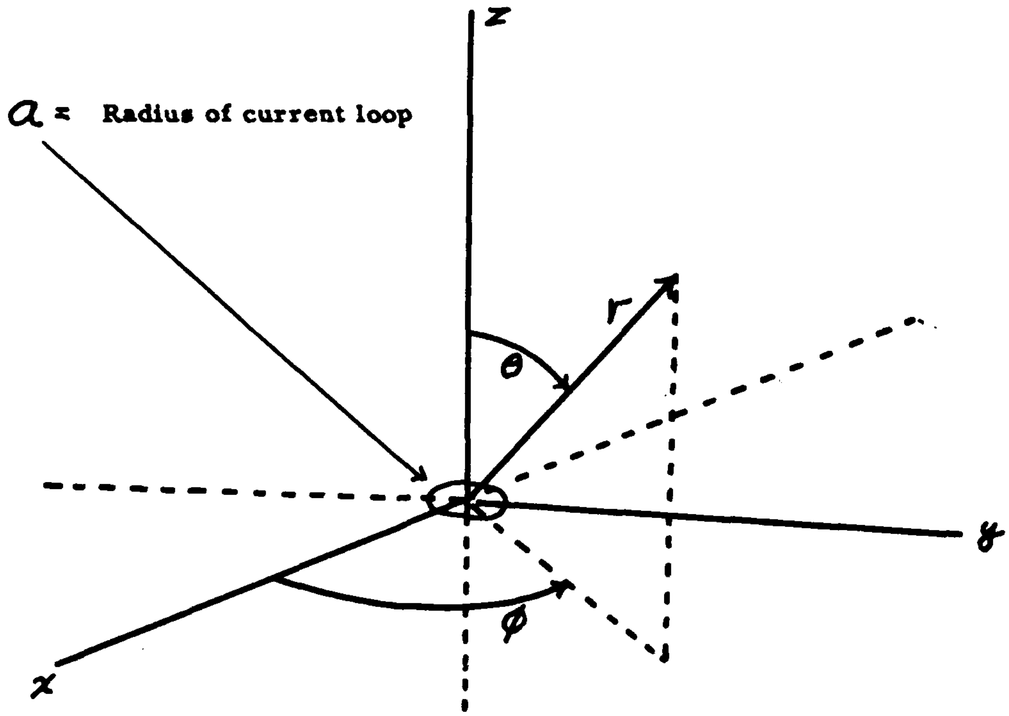
[7]Reference 6: p. 320.

[8]Reference 5: p. 270.

[9]Reference 7: p. 5.



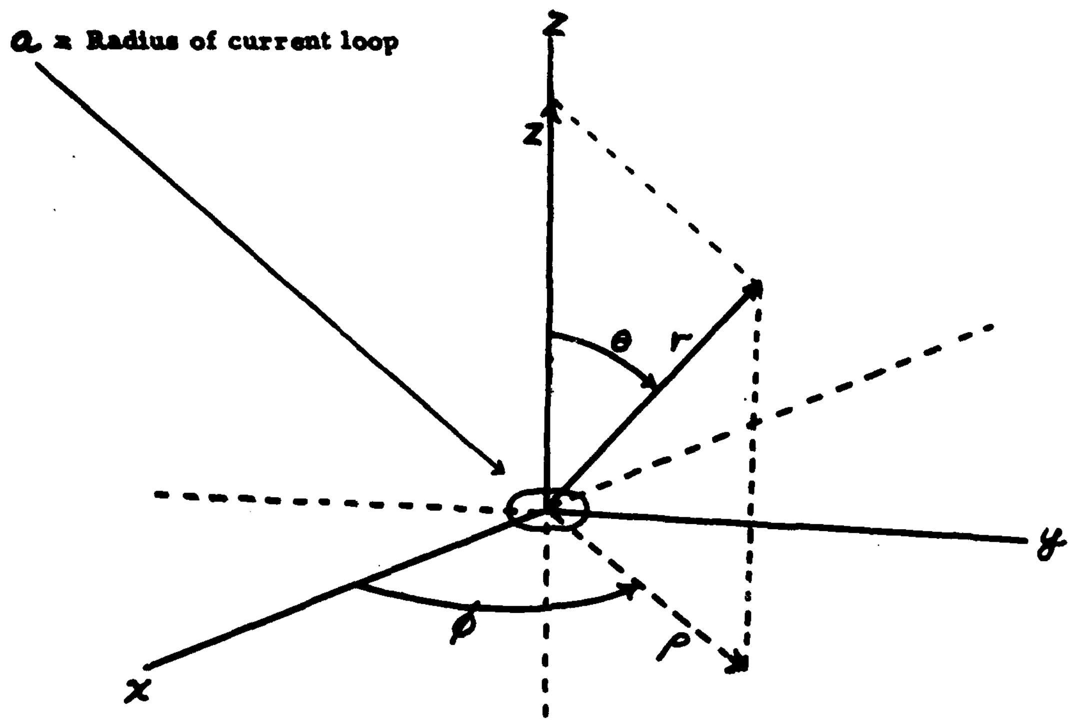
$$E_\phi = \frac{\gamma \mu \omega a^2 I}{4r}\left[1 + \frac{1}{j\gamma r}\right] e^{-j\gamma r} \sin\theta$$

$$H_\theta = \frac{-\gamma^2 I a^2}{4r}\left[1 + \frac{1}{j\gamma r} + \frac{1}{(j\gamma r)^2}\right] e^{-j\gamma r} \sin\theta$$

$$H_r = \frac{-\gamma^2 I a^2}{2r}\left[\frac{1}{j\gamma r} + \frac{1}{(j\gamma r)^2}\right] e^{-j\gamma r} \cos\theta$$

$$Z_w = \left|\frac{E_\phi}{H_\theta}\right| = \omega \mu r$$

FIGURE 4. FIELDS DUE TO LOOP (DIPOLE APPROXIMATION)



$$K = \int_0^{\pi/2} \frac{d\theta}{(1-k^2\sin^2\theta)^{1/2}} \qquad E = \int_0^{\pi/2} (1-k^2\sin^2\theta)^{1/2}\, d\theta$$

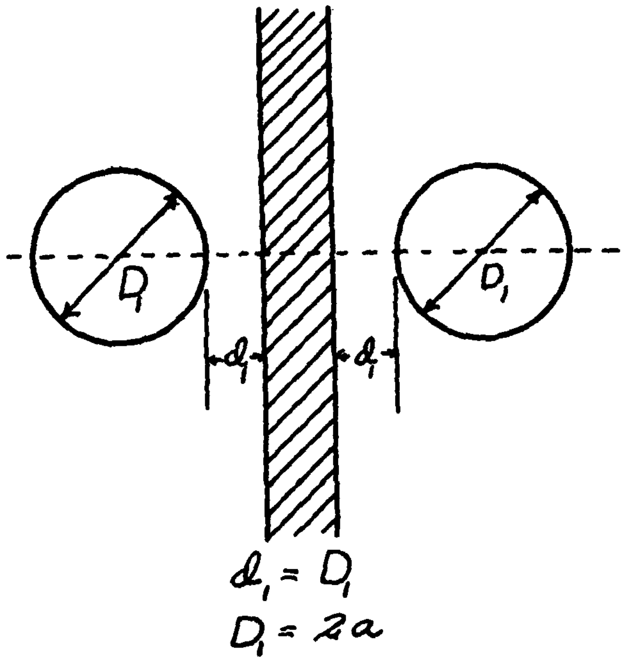
$$k^2 = 4a\rho\left[(a+\rho)^2+z^2\right]^{-1}$$

$$H_\rho = \frac{I z}{2\pi\rho\left[(a+\rho)^2+z^2\right]^{1/2}}\left[-K + \frac{a^2+\rho^2+z^2}{(a-\rho)^2+z^2}E\right]$$

$$H_z = \frac{I}{2\pi\left[(a+\rho)^2+z^2\right]^{1/2}}\left[K + \frac{a^2-\rho^2-z^2}{(a-\rho)^2+z^2}E\right]$$

$$E_\phi = \frac{j\mu I\omega}{\pi k}\left(\frac{a}{\rho}\right)^{1/2}\left[\left(1-\frac{1}{2}k^2\right)K - E\right]$$

FIGURE 5. FIELD DUE TO LOOP (LOW FREQUENCY APPROXIMATION)



Frequency ranges 150-200 kilocycles

FIGURE 6. SHIELDING TESTS USING LOOPS

Dipole Approximation

(31) $$Z_{WD} = -j\,\omega\mu\rho$$

Low-frequency Approximation

(32) $$Z_{WLF} = \mu\omega\,\frac{(a+\rho)^2}{\rho}\,\frac{\left[\frac{a^2+\rho^2}{(a+\rho)^2}K - E\right]}{\left[K - \frac{\rho+a}{\rho-a}E\right]}$$

which for $a \ll \rho$, reduces to Z_{WD}.

For the conditions of the test (Reference 7), at the shield $\rho = 3a$ which yields

(33) $$Z_{WD} = -j\mu\omega 3a$$

(34) $$Z_{WLF} = j\,\frac{16}{3}\,\mu\omega a\,\frac{\frac{5}{8}K - E}{K - 2E}$$

For $\rho = 3a$, $k^2 = .75$, which gives for the impedances

(35) $$Z_{WD} = -3j\,\omega\mu a$$

(36) $$Z_{WLF} = -2.88\,j\,\omega\mu a$$

This demonstrates that the error involved in using the dipole approximation to estimate the impedance of a loop, even at close distances, is small. The

situation has been investigated only in the $Z = 0$ plane.

b. High Impedance Sources

A typical source of a high impedance wave is a current element which is short compared to a wavelength. The field due to such an element is given in the literature and is shown in Figure 7[10]. The formulae for the fields and wave impedance shown in Figure 7 indicate that at close distances the wave impedance becomes high. These formulae are derived using the dipole approximation which, as in the case of the loop, are valid at distances from the dipole which are several times the length of the dipole. This source is also used in MIL-STD-285 tests to evaluate the performance of the enclosure against high impedance fields.

c. Plane-wave Impedance Sources

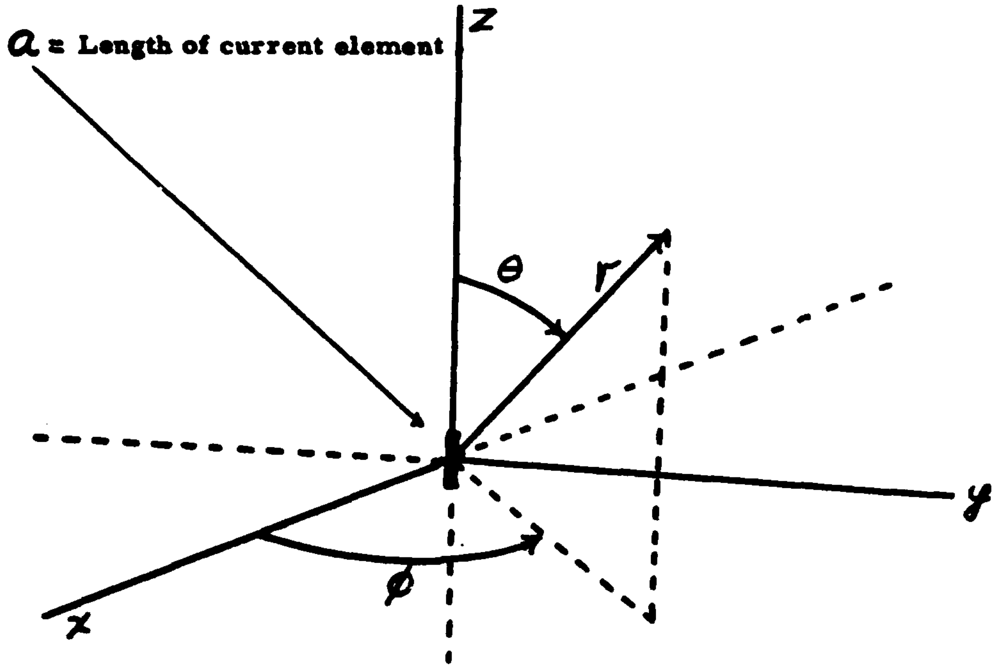
It is well known that in air a uniform plane wave can be obtained from any source configuration provided that the source is at a location removed from the wave front by a distance r very large compared with the wavelength λ. This plane wave exhibits a fixed impedance known to be 377 ohms.

It is somewhat less well known that a uniform plane wave can be established at distances small compared with the wavelength, provided only that the source configuration be properly chosen. For instance, such a uniform plane wave can be generated by an infinite plane current sheet of uniform density[11].

For shielding tests at the higher frequencies, the source configuration is not critical since it is practical to operate the source at an adequate distance from the shield such that $r \gg \lambda$. However, it is impractical

[10] Reference 6, p. 119.

[11] Reference 3, pp. 244, 245.



$$E_\theta = \frac{j\omega\mu}{4\pi r} I a \left[1 + \frac{1}{j\gamma r} + \frac{1}{(j\gamma r)^2} \right] e^{-j\gamma r} \sin\theta$$

$$H_\phi = \frac{j\gamma}{4\pi r} I a \left[1 + \frac{1}{j\gamma r} \right] e^{-j\gamma r} \sin\theta$$

$$E_r = \frac{j\omega\mu}{2\pi r} I a \left[\frac{1}{j\gamma r} + \frac{1}{(j\gamma r)^2} \right] e^{-j\gamma r} \cos\theta$$

$$Z_w = \left| \frac{E_\theta}{H_\phi} \right| = \frac{\mu\omega}{\gamma^2 r}$$

FIGURE 7. FIELDS DUE TO SHORT CURRENT ELEMENT (DIPOLE APPROXIMATION)

to meet this condition at the lower frequencies. The only possibility for obtaining a uniform plane wave lies in use of a special source configuration, but the infinite plane sheet of uniform current density is also impractical. Over the localized extent of the shield, however, the effect of an infinite plane current sheet might be approximated in various ways, including:

(a) a finite plane sheet of uniform current density placed sufficiently close to the shield that edge effects are negligible (Figure 8 (a)),

(b) a finite plane sheet of current density distributed to compensate for edge effects (Figure 8 (b)),

(c) a finite sheet of uniform current density with the sheet shaped in a manner to compensate for edge effects (Figure 8 (c)),

(d) a transmission line consisting of a pair of plane parallel sheets[12] (Figure 9),

(e) various combinations of these approaches.

Of all the approaches, the most promising for practical application appear to be given both by Figure 8 (a) and Figure 9. Calculations are now underway to estimate how close case (a) of Figure 8 approximates a uniform plane wave generator.

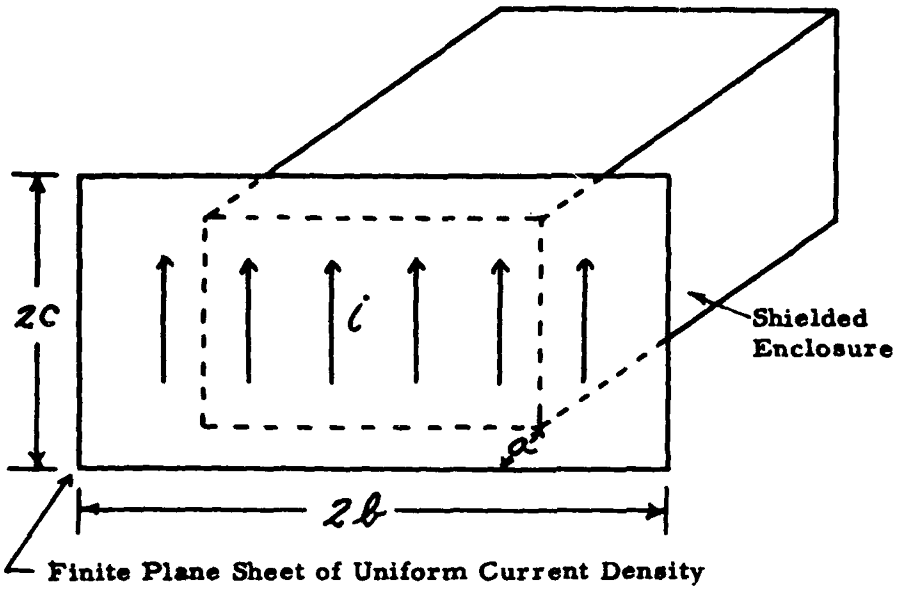
In practical application of any of these approaches to measurements of shielding effectiveness, it is anticipated that sheets of metal would not be required, but that a reasonably close approximation would be obtained with a moderate number of parallel wires or wire mesh as indicated in Figure 10.

C. Experimental Investigation

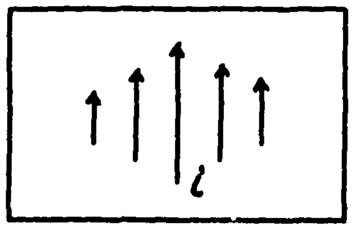
1. Coaxial Method for Materials Testing

It has been indicated that one approach to the problem of testing would be to employ a standard electromagnetic field and use the results of

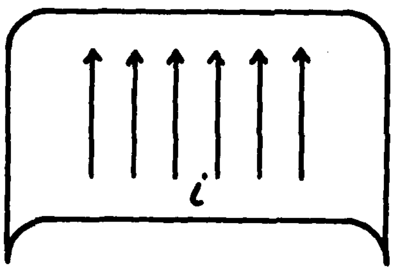
[12] Reference 3, p. 243.



(A) Finite Plane Sheet of Uniform Current Density Close to Shielded Enclosure

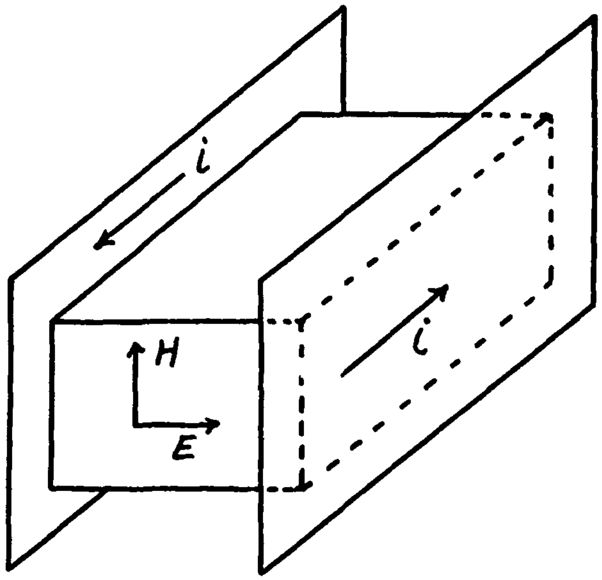


(B) Finite Plane Sheet of Distributed Current Density

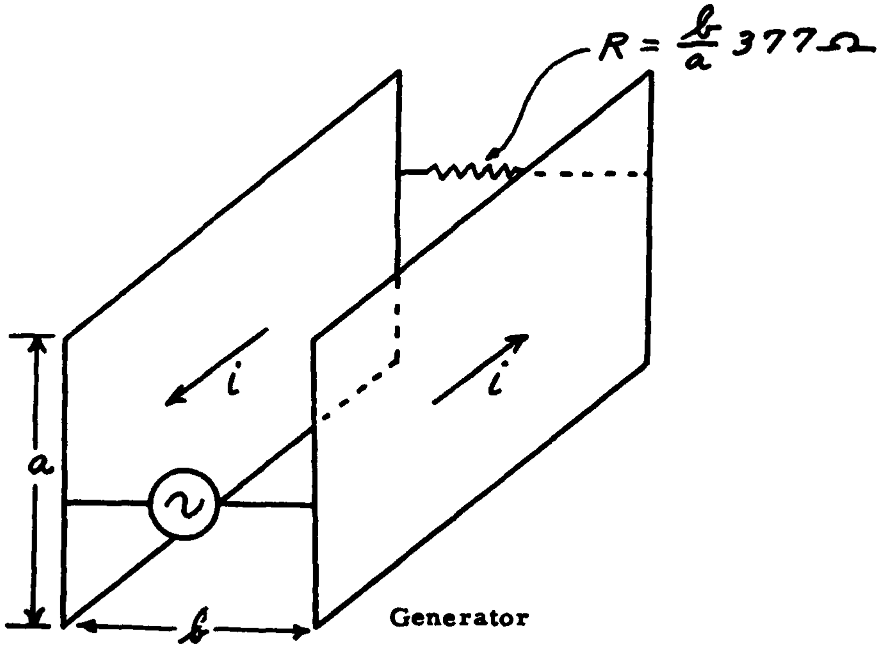


(C) Shaped Finite Sheet of Uniform Current Density

FIGURE 8. TECHNIQUES FOR GENERATING PLANE WAVES IN CLOSE PROXIMITY TO SOURCE



(A) Arrangement with Respect to Shielded Enclosure



(B) Circuitry

FIGURE 9. PAIR OF PLANE, PARALLEL SHEETS

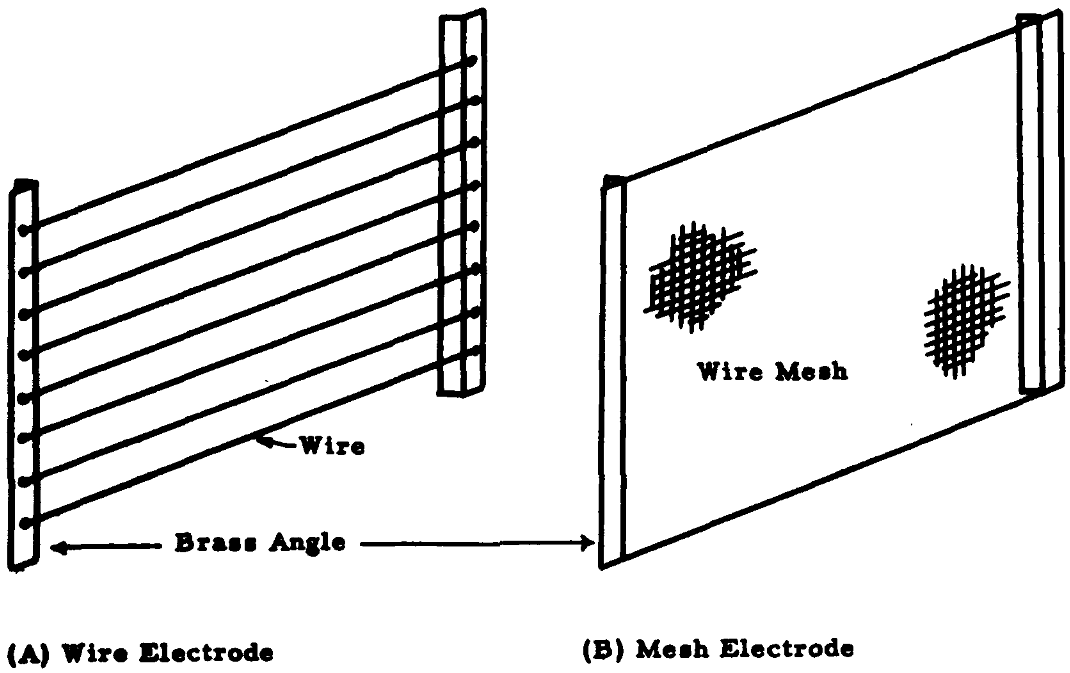


FIGURE 10. SOURCE ELECTRODE OF PARALLEL WIRES

the test to predict shielding effectiveness under other conditions. One such standard field is that associated with a plane-wave. A field which has the same impedance as a plane-wave is the TEM mode in a coaxial waveguide. The advantage of using a coaxial structure to test the shielding effectiveness of materials is that the fields are confined and geometrically simple. It is believed that this coaxial method of testing can also be used to evaluate the effectiveness of various types of joints used in shielded enclosures.

Maxwell's equations reduce to a simple form for the TEM mode (which is circularly symmetric)

$$\frac{\partial H_\phi}{\partial z} = -(\sigma + j\omega\epsilon)E_\rho \tag{37}$$

$$\frac{\partial}{\partial \rho}(\rho H_\phi) = 0 \tag{38}$$

$$-\frac{\partial E_\rho}{\partial z} = j\omega\mu H_\phi \tag{39}$$

The solution to these partial differential equations indicate that H_ϕ has the form

$$H_\phi = \frac{1}{\rho}\left[H_\phi^- e^{-j\gamma z} + H_\phi^+ e^{+j\gamma z}\right] \tag{40}$$

and the impedance of the wave in the region between the coaxial cylinders $(\sigma = 0)$

is given by

(41) $$|Z_w| = \sqrt{\mu/\epsilon}$$

This is the impedance of a plane-wave and it does not vary with the location between the cylinders. It can further be demonstrated that the equations which govern the passage of a plane-wave through an infinite planar sheet apply to the passage of the TEM wave through a planar barrier in the coaxial structure. Consequently, measurements of the shielding effectiveness of materials using the TEM mode in a coaxial structure is equivalent to using a plane-wave and infinite planar sheet.

The voltage across the coaxial struture is the line integral of the radial electric field; consequently, measurements of voltage across the coaxial line are equivalent to measurements of the electric field intensity. This affords a simple means of measuring the intensity of the waves which impinge upon and are transmitted through the shielding barrier.

An experimental device has been constructed to examine the coaxial method of testing and is shown in Figure 11. The shielding effectiveness of the barrier is determined by connecting a source to one end of the coaxial device and a detector to the other and measuring the voltage corresponding to the transmitted wave. The source is then connected directly to the detector through an attenuator and sufficient attenuation is inserted to yield the same voltage as that which was measured through this shielding barrier. The amount of attenuation needed is equal to that afforded by the barrier.

The test is most easily performed if the source and detector impedances are equal to the characteristic impedance of the coaxial device. This is best accomplished by using pads (attenuators) to isolate the coaxial device from the source and detector. The Rollins Standard Signal Generators will be

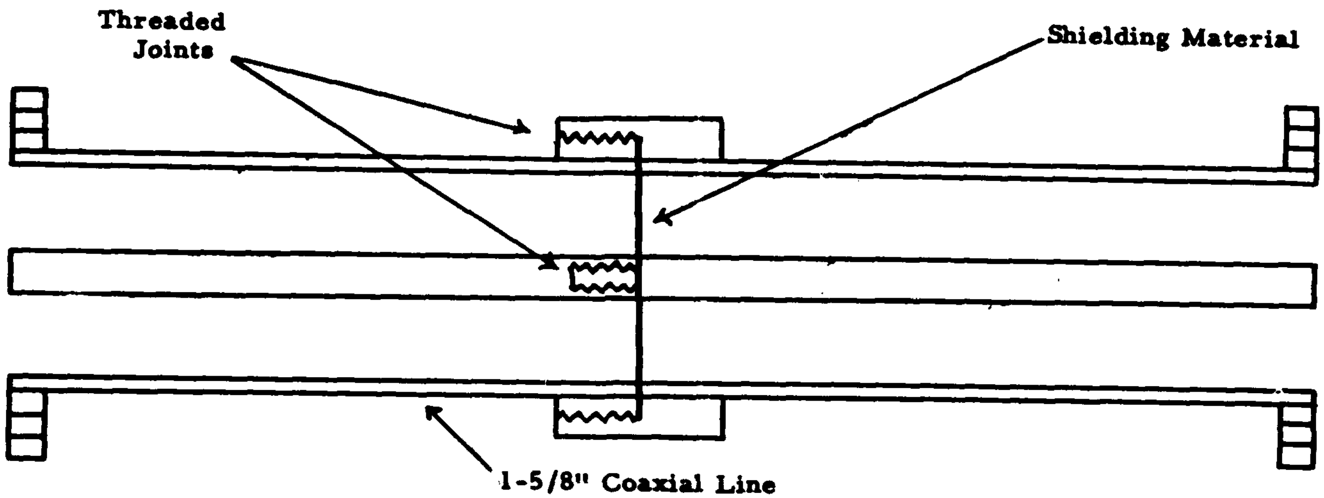


FIGURE 11. CROSS-SECTIONAL VIEW OF COAXIAL TESTING DEVICE

used as sources and radio-interference meters as detectors.

2. Construction of Test Equipment for Evaluating Shielded Enclosures

During this quarter, all special test equipment specified in MIL-STD-285 has been constructed in preparation for shielding tests as presently specified. It is anticipated that tests made in this manner will be used as a comparison with tests to be developed later.

D. Project Performance and Schedule Chart

The scheduling of the program of research is shown in Figure 12. The open areas represent planned effort while the shaded areas represent completed work. The financial status of the project is as follows:

For the period ending 30 November 1958*

Original money allocated for research	$37,672
Total expenditures	7,105
Total commitments	126
Balance available for research	$30,441

It is anticipated that the expenditures for December 1958 will be approximately $4,000.

CONCLUSIONS

1. The plane-wave theory of shielding provides the basis for the bulk of shielding theory. Its usefulness in predicting the effectiveness of shielded enclosures, especially at the lower frequencies, is questionable.

2. The transmission-line analogy provides a useful means for interpreting and extending the results of plane-wave shielding theory. The extensions obtained thus far could have been obtained directly from the plane-wave theory.

*Cost sheets for December 1958 are not available until January 20, 1959.

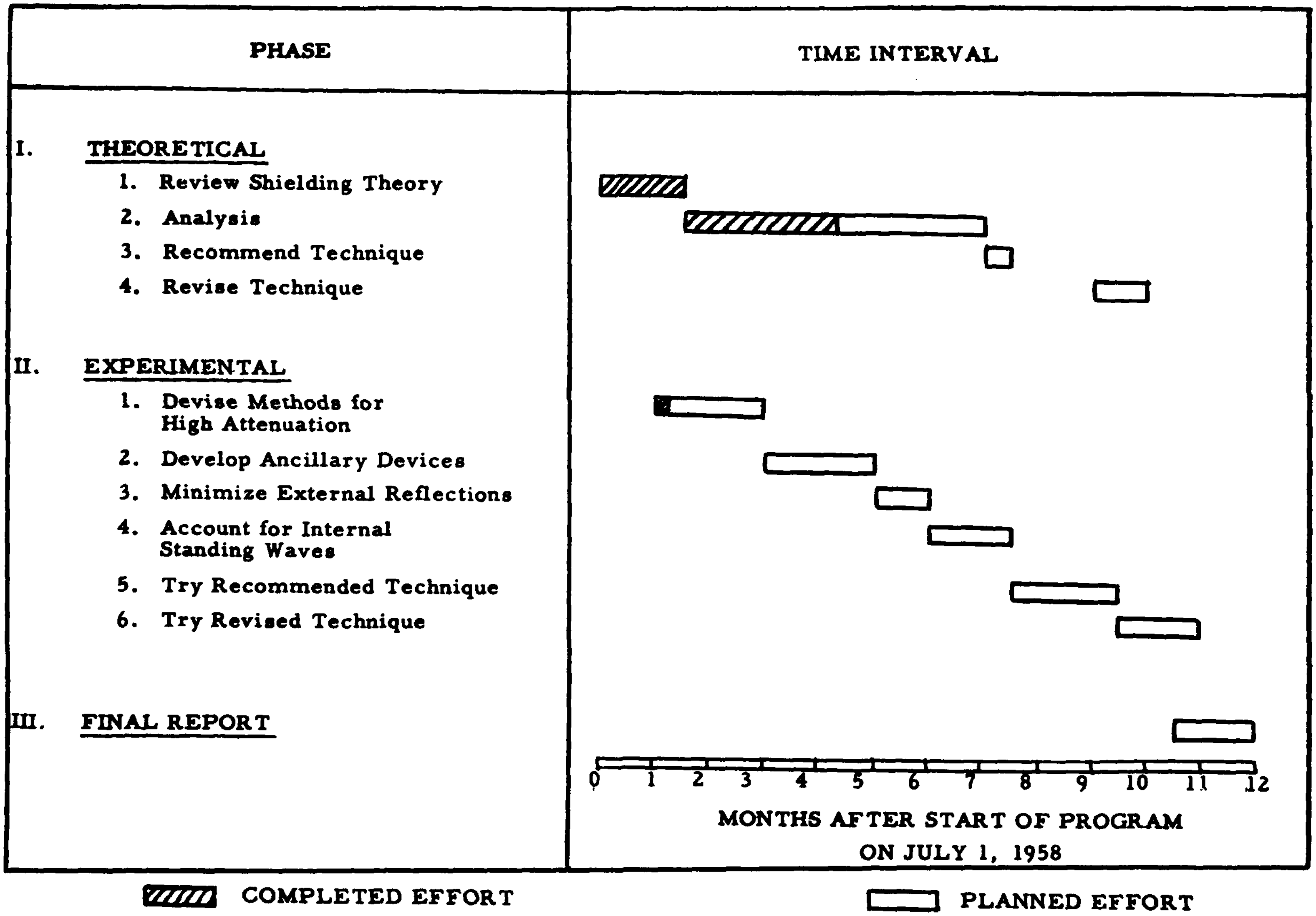


FIGURE 12. PROJECT SCHEDULE CHART

3. Analysis involving the use of mode functions has resulted in formulae giving the penetration of plane-wave fields into conducting shells having regular geometrical shapes and dimensions small compared to a wavelength.

4. One theory of shielding makes use of moving images to replace eddy currents. The result of this analysis is an integral expression for the induced vector potential.

5. It appears that a coaxial structure will be useful in evaluating the effects of door and wall joints and the effectiveness of both homogeneous and non-homogeneous shielding materials. There is, however, insufficient experimental data available at this time to substantiate this conclusion.

PROGRAM FOR NEXT INTERVAL

During the next quarterly period, effort will be expended on the following aspects of the program:

1. The review of shielding theory will be continued.

2. The analytical investigation of tests employed in the present MIL-ST-285 will be initiated.

3. Experimental investigation of the coaxial device for evaluating shielding material will be continued.

4. Methods for achieving greater dynamic range of testing equipment will be investigated.

Respectfully submitted,

ARMOUR RESEARCH FOUNDATION
of Illinois Institute of Technology

L. C. Peach

L. C. Peach, Research Engineer

H. M. Sachs

H. M. Sachs, Assistant Supervisor
Electronic Interference Section

APPROVED:

S. I. Cohn

S. I. Cohn, Assistant Manager
Electrical Engineering Research